CO2CirculAir
Smart Direct Air Capture

SMART-DAC

Net Zero Technology Centre
Technology Driving Transition

Department for Energy Security & Net Zero

SMART-DAC (CO2202035)
GGR Innovation Programme

Phase 2 Public Report
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Executive summary

The SMART-DAC (Sustainable Membrane Absorption & Regeneration Technology for Direct Air Capture) project has demonstrated significant potential in advancing direct air capture technology. Through its innovative approach CO2CirculAir has made substantial progress in developing a cost-effective and efficient carbon capture system, with promising prospects for commercialisation and large-scale deployment for both Carbon Capture and Storage (CCS) and Utilisation (CCU) applications such as use in horticulture, food and beverage industries and potentially the biggest market as a feedstock for synthetic fuels.

With first CO_2 captured in September 2023 it has had an operational uptime of > 80% over a 19 month period to April 25.

Developed by CO2CirculAir and funded under the Greenhouse Gas Removal (GGR) Programme from the Department of Energy Security and Net Zero (DESNZ), SMART-DAC offers a novel passive wind driven direct air capture (DAC) system. The technology features a two-step process: a natural wind driven absorption of CO_2 using a potassium hydroxide (KOH) based solution and regeneration through membrane electrolysis/electrodialysis producing a pure and green CO_2.

SMART-DAC has been designed around modularity, low cost materials, simplicity of operation and mechanical parts, and the flexibility to harness green energy or when surplus energy is available at low cost, making it an affordable solution to industries where cost margins are low. This approach has many advantages over existing DAC systems in that it is,

- Environmentally friendly by using a non-toxic chemically stable fully regenerable solvent
- No heat is required to separate the CO_2 from the solvent resulting in a low energy penalty and optimising efficiency
- The chemically inert process allows construction using low cost fully recyclable plastics reducing unit costs.
- A Smart Buffer System allows continuous absorption of CO_2 without having to stop for regeneration.
- The low energy electrodialysis regeneration system enables the use of renewable energy giving SMART-DAC an 88% efficiency in that 1 kg of CO_2 captured emits only 0.124 kg of CO_2

The pilot plant, located in Larne, Northern Ireland, demonstrated the system's viability and capture rates of 100 tonnes of CO_2 per annum. The plant's modular design facilitated testing different configurations for optimal performance. The project's learnings, including membrane materials, system resilience and operation in various weather conditions, provided critical insights for future scaling.

Data recorded show very encouraging results with flux rates of 2grCO_2/m^2/hr (required rate based on the design parameters of the pilot plant to capture 100 tonnes per annum) being achieved at average wind speeds as low as 8-10mph and approaching 3grCO_2/m^2/hr towards the end of November 2024 where average wind speeds were recorded between 15-23mph. A maximum flux rate of over 8grCO_2/m^2/hr was recorded during Storm Darragh in December 2024.

Operation during the storm was one of the key findings from the project. The membranes and modules suffered virtually no damage during the storm demonstrating that the membranes are extremely robust and can withstand very high winds potentially widening the operational window of SMART-DAC than initially considered at the start of the project.

Tests carried out to understand the energy consumption of the regeneration process were also very encouraging. Based on the data recorded and data analysis it is projected that it is possible to achieve an energy consumption of less than 2.5kWh per kg of CO_2 captured.

Using these projections and extrapolated data from the pilot plant techno economic analysis was carried out for scaling up to a 10,000 tonnes per annum plant. The results demonstrate that a range of £400 - £500 per tonne of CO_2 could be achieved. Considering the calculations are founded on data from the pilot plant these results are very promising, suggesting that as SMART-DAC moves from the innovation space to commercialisation through targeted optimisation and development, and achieving economies of scale through multiple deployments or larger plants this will reduce the price per tonne.

Commercialisation efforts focus on utilising captured CO_2 in various markets, including e-fuels, green chemicals, and agricultural applications. Collaborating with partners, B9 Energy (Larne, Norther Ireland) and Catagen (Belfast, Northern Ireland), CO2CirculAir is poised to address market demands with flexible, location-specific solutions.

The financial model projects SMART-DAC reaching TRL8/9 by 2026, generating significant revenue from 2027 onwards. Continued innovation and strategic partnerships will be crucial for overcoming barriers and achieving large-scale deployment, ultimately contributing to global carbon reduction efforts.

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Introduction

With increasing concerns relating to the climate emergency, there is a growing acceptance of the urgent need to reduce CO_2 emissions rapidly and substantially. This creates opportunities in relation to the development and deployment of carbon capture technologies in the UK. In 2021 the Committee for Climate Change (CCC) identified CCS as an essential component of the 'balanced pathway' to meeting the UK's net zero goals. It is a necessity if the UK is to meet its target of storing 20-30 Mt per annum of CO_2 by 2030 (equivalent to 12 million cars off the road) and net zero by 2050.

CCS is normally associated with decarbonising hard to abate industries such as steel, cement, refining chemicals, glass and ceramics, which all emit CO_2 as part of a chemical process required in production. CCS is also a means to complement renewable energy generation, access to low-carbon dispatchable power (Power CCS) will be essential to balance the intermittency of renewables.

As well as removing industrial and power emissions, CCS has the potential to produce net-negative emissions through engineered carbon removal process such as bio-energy carbon capture and storage (BECCS) and direct air capture and storage (DACS). GGR technologies like these will be essential to address residual and legacy emissions. With the UK government's ambition to capture 23 $MtCO_2$ of engineered carbon removals per annum by 2035, it is imperative that existing technologies are proven in the field and new technologies are de-risked and demonstrated. The GGR sector also represents a major economic opportunity for the UK. The CO_2 produced from GGR technologies like DAC together with green hydrogen can be used as a feedstock for the production of low carbon synthetic fuels as well as a feedstock in the production of low carbon chemicals, generating the development of green jobs across the UK and in the export of knowledge, technology and intellectual property.

Although CCUS is not new with technologies technically and commercially available, one of the main barriers to widespread adoption is the high cost of capture especially in processes like direct air capture where the volume of CO_2 in the air is low compared to industrial or power capture. A report issued by the Net Zero Technology Centre identified key areas where innovation and new technologies could help to reduce the current cost of carbon capture and utilisation. These centre around the capture materials (sorbents, membranes) for high-capacity CO_2 capture with minimum energy requirements for regeneration, low toxicity and long lifetime, and high CO_2 conversion efficiency for low-cost pathways to CO_2 utilisation. Significantly reducing the cost of carbon capture technology will drive growth and scale within the industry, allowing feasible business models, creating new low-carbon products from using the captured CO_2 as feedstock, and generating jobs to support the new industries. With a gap in the market the UK could position itself as a centre of excellence and innovation promoting itself at the forefront of GGR technologies.

To achieve this DESNZ (Department of Energy Security and Net Zero) set up the Net Zero Innovation Portfolio (NZIP). This is a £1 billion fund designed to accelerate the commercialisation of low carbon technologies across multiple sectors. Within NZIP the GGR Innovation Programme was created with the aim to identify technologies which remove CO_2 or other Greenhouse Gases (GHGs) from the atmosphere and drive innovation in these through targeted design and demonstration at pilot scale. While pilots

and demonstrators will initially be small scale and may not reflect the cost of capture at scale, the ultimate objective of the programme is to identify one or more ways in which to achieve removals at the $MtCO_2e$ scale or greater, at a cost of <£200 per tonne CO_2e removed.

This report details a novel direct air capture technology, SMART-DAC, designed by CO2CirculAir which has received funding through the GGR Programme to deliver a pilot plant that can demonstrate capture of CO_2 from the atmosphere at a rate of 100 tonnes per annum.

1.1 SMART-DAC Concept

The novel SMART-DAC process is based on a two-step process:

a) Natural wind driven absorption of CO_2 from air by membrane gas absorption (MGA) using a potassium hydroxide (KOH) based solution absorbent

b) Regeneration of the absorbent by membrane electrolysis/electrodialysis (ME/ED) and at the same time producing a pure and green CO_2.

MGA uses a membrane to keep the air (gas) and liquid absorbent phases separated while allowing mass transfer between gas and liquid phases. The KOH (1 to 2 molar (mol/L)) absorbs the CO_2 from the air as it passes through the membrane and reacts with CO_2 to form potassium (bi)carbonate (K_2CO_3/$KHCO_3$). In the regeneration step electrodialysis with bipolar membranes is used to convert the carbonate back into KOH for reuse as an absorbent and release the captured CO_2.

Natural wind circulation is used, as opposed to turbines used in most of the current DAC systems, for contacting and the flow of air through the membranes reducing the energy for absorption to practically zero. Power, in the form of renewable electricity, will only be required for the electrochemical regeneration process of the used absorption material.

A ‘smart’ tanker storage system has been built into the design to maximise operational performance. The storage system will allow the MGA and ED processes to operate separately managing operational down time and periods of low passage of air through the system to enable continuous and efficient operations. This will also offer the flexibility in the system to run in periods of low-cost surplus electricity or by direct use of green electricity from solar or wind powered sources. A simplified process flow diagram for the SMART-DAC concept is illustrated below in **Figure 1**.

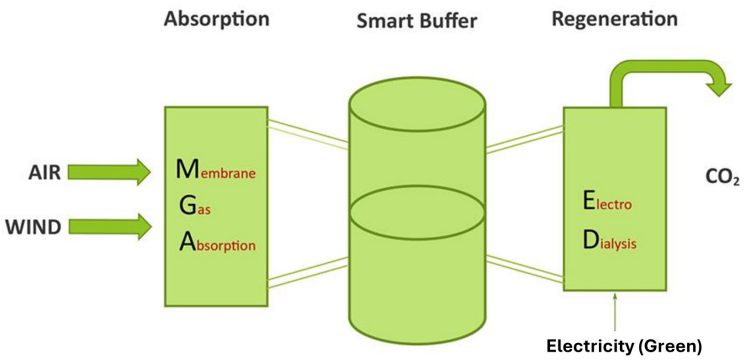

Figure 1: Simplified process flow diagram of the SMART-DAC concept

1.1.1 Membrane Gas Absorption

Membrane Gas Absorption (MGA) uses a membrane to keep gas and liquid phases separated while allowing mass transfer between the phases. The membrane creates the required surface area for mass transfer between the gas and liquid phases, **Figure 2**.

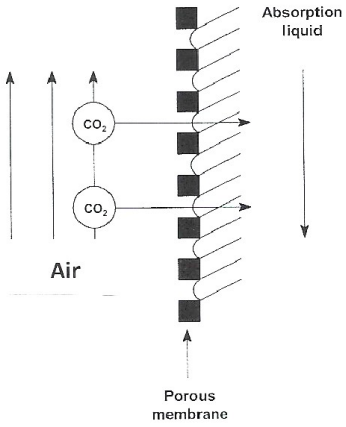

Figure 2: Principle of membrane gas absorption

MGA is a proven technology and has extensively been studied, tested, and used in gas separation processes including the absorption of CO_2 from flue gases. Application for DAC requires a specialised design of the absorption modules to account for the low concentration of CO_2 in the air and in the case of SMART-DAC to allow the natural flow of air through the module. An important breakthrough in this project is the use of thin hollow fibre membranes strengthened to withstand strong winds which allow an increased surface area for mass transfer.

Additionally, it has been found that the use of common amine-based absorbents cause leakage. SMART-DAC overcomes this through the application of a safe absorbent which uses a fully inorganic absorbent (KOH) which is chemically stable, non-volatile, non toxic and regenerable without loses. This is a clear benefit to both the environment and running cost of SMART-DAC compared to the use of amines which can be toxic and degrade through use. In combination with hydrophobic membranes, KOH has several advantages of which the most important is that wetting of the membranes is less likely. The absorbent has been shown to be fully compatible with regular commercially available microporous membranes but has not been applied for direct air capture until this project.

In the SMART-DAC pilot plant a series of modules have been built to house the membranes. The mass transfer coefficient determines the total capacity for absorption of CO_2 in the MGA module, together with the available surface area for mass transfer and the differential in the concentration of CO_2 in the air and absorbent. Therefore, to maintain CO_2 absorption there must always be a minimum CO_2 concentration gradient across the membrane and therefore only partial CO_2 depletion from the air feed is possible.

Absorption of CO_2 happens in a two-step process. As the CO_2 comes into contact with the alkaline (pH 14) KOH solution potassium carbonate is formed (K_2CO_3) reducing the pH. With continued absorption of CO_2 and decrease in pH the reaction changes to the formation of potassium bicarbonate ($KHCO_2$). This second reaction occurs around pH 10 and is significantly slower than the conversion to potassium carbonate. Continuing the reaction to potassium bicarbonate requires longer residence times impacting efficiency

and costs, therefore the absorption process is stopped on reaching a pH of between 11-10.

1.1.2 Electrodialysis with Bipolar Membranes

Once the CO_2 from the air has been captured through the MGA units the CO_2 rich solvent passes into the regeneration unit where the electrodialysis bipolar membrane (EDBP) unit recovers the KOH from the K_2CO_3 formed during the absorption process and releases the captured CO_2.

EDBP is an innovative and efficient technology that combines the principles of traditional electrodialysis with the unique capabilities of bipolar membranes. This process is particularly notable for its ability to split water into hydrogen and hydroxide ions, enabling the direct production of acids and bases from salts. Commonly used in waste water treatment its application is becoming more widespread in the production of acids and bases, in the food and pharmaceutical industries and is gaining considerable interest and research in application of recovering valuable resources like ammonia, nitrogen and CO_2 from various processes.

EDBP have a number of advantages over traditional electrodialysis due to its versatility and is more energy efficient and therefore more cost effective solution making it suitable to be powered by renewable energy sources such as wind or solar. It is also considered to be more environmentally friendly due to its lower energy consumption and reduced chemical usage. Additionally, it does not produce gases as byproducts, which simplifies the process and reduces safety concerns.

In the SMART-DAC unit a two compartment cell is used consisting of bipolar and cation-selective membranes as illustrated in **Figure 3** below**.**

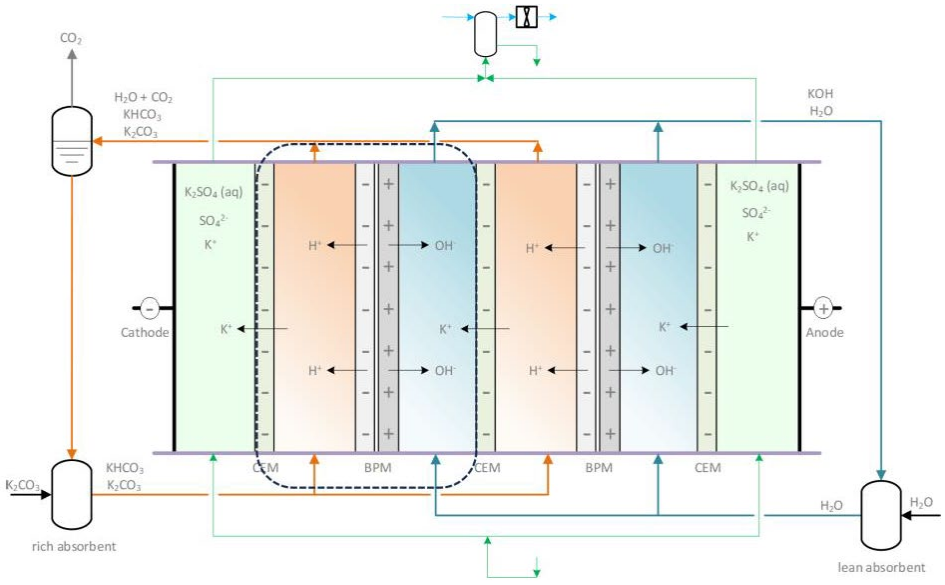

Figure 3: Simplified schematic of the EDBP process

The loaded absorption fluid from the MGA unit, a solution of about 0.5-1 molar (mol/L) K_2CO_3, is pumped into the EDBP unit. The potassium (K+) ion will be attracted by the cathode and pass the cation-selective membrane where they will react with the OH- from the bipolar membranes to be transformed in KOH.

At the anode side the remaining CO_3 ions will react with the H+ produced from water splitting in the bipolar membrane to form H_2O and CO_2.

An aqueous 5% K_2SO_4 solution has been defined as the electrolyte, which continuously circulates between the anode and cathode compartments. By using an aqueous electrolyte at the anode and cathode compartments of the electrodialysis unit the composition will remain mostly unchanged. The concentration may slightly increase due to water electrolysis and a regular feed of demi water will be needed.

The use of bipolar membranes significantly reduces the energy penalty of the regeneration process compared to standard electrodialysis. Since water splitting occurs in the bipolar membranes, at a relatively low voltage, no H_2 and O_2 gas is formed (or only in minute amounts).

On top of the reduction in energy using the EDBP unit gives greater flexibility in the operation of the pilot plant. It creates the potential to cease the absorption process at a higher pH leaving a mixture of carbonate and bicarbonate in the absorbent with a lower residence time in the absorber. If low-cost electricity is available this can reduce CAPEX as the plant can be designed with fewer absorption modules.

1.1.3 Pilot Plant Location

The pilot plant is located at the offices of B9 Energy Ltd in Larne, Northern Ireland. Located to the north of Belfast and adjacent to the Port of Larne the site offers excellent transport and supply chain links to facilitate the operation of the pilot plant.

Located to the north of Belfast, the Port of Larne was one of the locations modelled by Heriot Watt during the wind profile analysis during Phase 1 of the GGR Programme (see Appendix 1: Weather conditions in Larne).

One of the attractive points of the SMART-DAC process is that natural wind is used as the main driving force for CO_2 capture, which means that there is no need for placing (electrical driven) blowers to direct the air through the MGA modules. Analysis shows that the area is very favourable for the location of SMART-DAC. The B9 office is located on an exposed site at 87m above sea level and so will see higher wind speeds as a result. The site already has a 6kW wind charger located on an 18m high tower, 12kW of roof mounted solar PV and a 3-phase grid connection with sufficient capacity to drive the SMART-DAC at any/all times of day.

Weather profiling analysis showed a prevailing wind direction from the south-west with an average yearly wind speed of 3 to 4 Beaufort (12-20mph). Average yearly temperatures range from 3-17^{o}C so protection against freezing of the KOH or components should not be required and this was found to be the case. Located in the west of the UK, average rainfall is slightly higher compared to the east of the UK but remains comfortably within the operating envelop of SMART-DAC.

The pilot plant has been installed north west to south east to align the MGA modules to the prevailing wind direction, **Figure 4**.

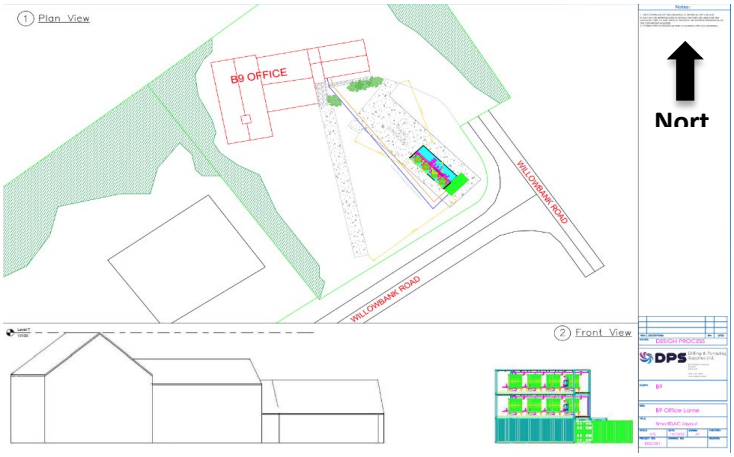

Figure 4: Plan and side views for the location of the pilot plant

There are some low lying trees on the edge of the site which had impact on the flow of air to the lower MGA unit but no impact on the upper unit. The neighbouring building and the B9 office buildings are not in line of sight of the pilot plant in the prevailing wind direction.

Figure 5 shows the fully constructed pilot plant on site in April 2024 (left) and January 2025 (right). The prevailing wind direction is from right to left in the pictures entering the pilot plant from the wind turbine side. As the pictures show there is good clearance around the pilot plant and the trees should offer minimal resistance to the air flow.

Figure 5: Full scale pilot plant on site in Larne, Northern Ireland

1 Pilot Plant Design

To achieve a minimum of 100 tonnes CO_2e per annum the capacity of the pilot plant has been designed to capture 0.314 tonnes CO_2 per day or 13.1 kg CO_2/hr. Based on 350 operational days, including a 10% overdesign margin, gives this a 110 tonnes per annum CO_2 capture capacity.

Figure 6 shows a 3D render of the pilot plant layout.

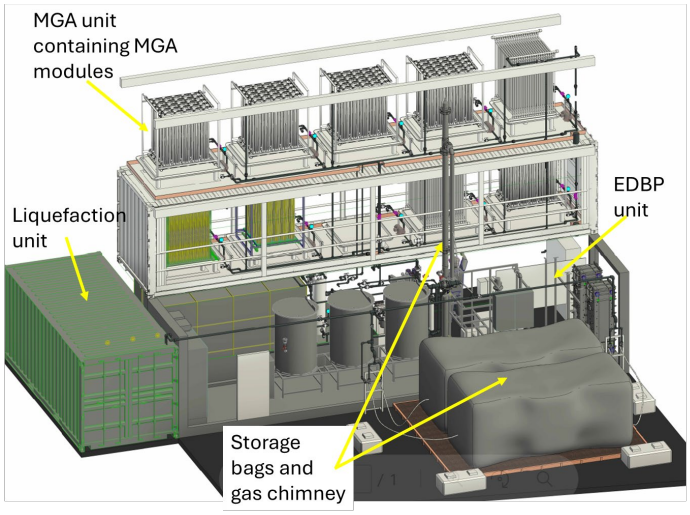

Figure 6: 3D view of the SMART-DAC System showing the two MGA units containing the MGA modules, the EDBP unit, the CO_2 chimney and CO_2 collection bags

The pilot plant is based on a modular container design. The MGA towers in the plant schematic have been designed into two 40ft shipping containers which sit on top of one another. Each container has been designed to house up to five MGA modules which sit on specially designed tables to allow ease of connection and operation. Design of the modules and layout of the MGA units will be discussed in detail in the next section. The regeneration unit (EDBP) is directly below the two MGA units, with the 'smart' buffer tanks in another container behind the EDBP unit. The smaller unit at the end of the main containers houses the liquefaction equipment to process the capture CO_2. The CO_2 chimney, installed in the dilute system of the EDBP, separates out the CO_2 which is then passed in the storage bags before liquefaction and bottling. The pilot plant is powered through the a 3-phase grid connection on site.

The modular construction allowed much of the manufacturing and construction effort to be completed "off-site" within a more controlled shop environment, increasing the likelihood of positive outcomes in terms of cost, schedule, and quality. This also simplifies decommissioning or re-use of the plant.

1.1 MGA Modules and Units

The MGA unit has been designed as a multistage recirculation (MSR) system consisting of a number of MGA modules which can be operated both in batch mode and continuous mode.

Small scale testing of the absorption capacity and velocity with hollow fibre modules in the laboratory has shown that an average loading velocity of approximately 2 $gCO_2/m^2/h$ can be reached for CO_2 absorption between pH14 and pH10.5-11. Below pH10.5 the absorption velocity decreases sharply due to the considerably slower reaction of CO_2 with carbonate into bicarbonate. Therefore, an absorption velocity of 2 $gCO_2/m^2/h$ has been taken as the design standard for the development of the membrane modules for the pilot plant.

The absorption capacity will also depend on the wind velocity. To achieve a CO_2 capture rate of 100 tonne CO_2/year (mean of 13.1kg/h) the total average wind velocity needs to be 3 Beaufort (about 5 m/s).

With the MGA modules being housed in 40ft shipping containers the dimensions and specifications of the modules are constrained by the size of the container (internal dimensions 12.02m long x 2.35m wide x 2.39m high), length of the membranes (~1.5m), surface area and the required air flow rate. The modules must have sufficient surface area and enough space must be left between membrane bundles to allow air to flow through the system to allow sufficient residence time of the air against the membranes.

At mean operational wind velocities of 5 m/s (approx. 10mph), the system would theoretically require between 8-9 modules to capture the required volume of CO_2. Higher wind velocities will result in decreased residence time of the air in the module and recovery but increased CO_2 capture due to a higher driving force for mass transfer with the higher average CO_2 concentration during passage through the module.

The MGA modules were constructed by fixing hollow fibre membranes into frames. For the initial modules two frame designs were considered; header frame and base plate, **Figure 7**.

Figure 7: Full scale MGA modules, header frame (left), base plate (right)

For the header frame design, a module consists of a series of linear frames with fibres attached to the specially designed frame. The module consists of 19 headers each holding 19 bundles, giving a total of 361 membrane bundles. The size of the module is approx. 1.7 x 1.6 x 1.8 m (LxBxH).

In the base plate design the hollow fibres are arranged on a plate in circles. The fibres are connected to the base through holes drilled in the base plate. The end of the of hollow

fibres are glued into a short piece of plastic pipe, which is pushed through the holes in the base plate and sealed in place with an O-ring.

As with the header frame each base plate consisted of 19 bundles but the configuration and size of the base plate design meant that the module consisted of 25 base plates giving a total of 475 membrane bundles and therefore roughly a 25% larger surface area.

Adopting a module based design approach allowed for the systematic testing of different module designs with differing numbers of bundles and separation between bundles and frames to understand the impact of membrane density and separation on the flow of air through the modules and therefore capture rate and efficiency of the system. This led to a number of different module configurations being installed in the pilot plant.

To protect the membranes from severe weather conditions as well as UV radiation louvers were installed on the open sides of the containers (**Figure 8 and Figure 9**). High winds (above 8 Beaufort) and debris might damage the membrane fibres and direct sunshine could cause a breakdown of the polymer structure of the fibres, both causing leakage of absorbent and loss of absorption capacity.

The louvres are controlled automatically via a weather station (installed on the top of the upper container). The weather station measures room temperature, outside temperature, brightness, wind speed and precipitation. When in automatic mode the weather station can control the aperture of the blinds to protect the membranes. For example, to protect the membranes from direct sunlight, the blinds will automatically manoeuvre to deflect the direct rays of the sun. Similarly, the system can be set to close or partially close the blinds depending on wind speed and direction. The blinds have been set to close to 60-70% of total opening once the wind speed reaches 15 m/s on the side of the wind direction.

Figure 8: Pilot plant in Larne with the 1st MGA unit installed with four MGA modules of type F2-F5 Modules have been placed with frames parallel to the prevailing wind direction

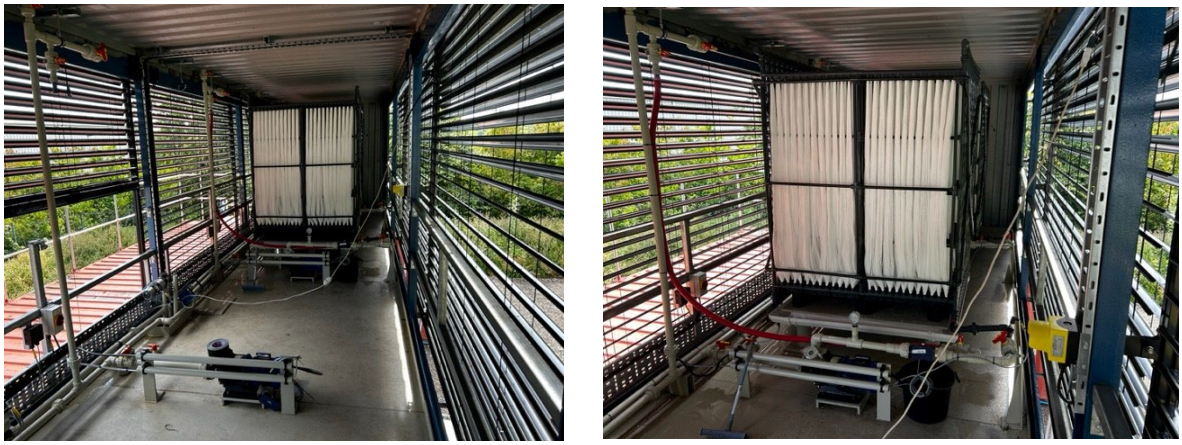

Figure 9: MGA Module inside unit. Louvers visible on side of container

While the louvers were effective in protecting the membranes from UV light they were found to not be sufficiently robust to withstand high winds sustaining considerable damage during storms in December 2024 and January 2025. The use and design of the louvers will be examined and revised for the next generation plant.

To collect any leakage of absorbent from the modules gutters were installed around the bottom of the modules. All leakage is collected, filtered to remove any fouling and then returned to absorbent tank. A bund has been placed on the bottom of the container for safety reasons.

To prevent rain water from entering the bund and diluting the absorbent, guttering has been installed on the top side of the containers as well as a protection cap over the Louvres.

1.2 Regeneration Unit – EDBP

The EDBP unit is part of the bigger SMART-DAC system focusing on the capture and production of the CO_2. The system has been designed so that the capacity of the EDBP is greater than the MGA section. This enables the EDBP and MGA sections to work independently to allow regeneration to take place when low cost electricity is available. The loaded absorbent can be stored in the built in tank set to be regenerated when the cost of electricity is low.

The unit has been sourced from MEGA, a specialist in waste water treatment and the provision of electrodialysis and bipolar membrane solutions. CO2CirculAir have worked closely with MEGA throughout the project to implement the design specifications for the ED ELPU-P15 unit which was installed in the pilot plant and will be briefly described below

The ED ELPU-P15 unit is contained within its own 40ft standard shipping container. **Figure 10** shows the arrangement within the container of the main components of the EDBP system.

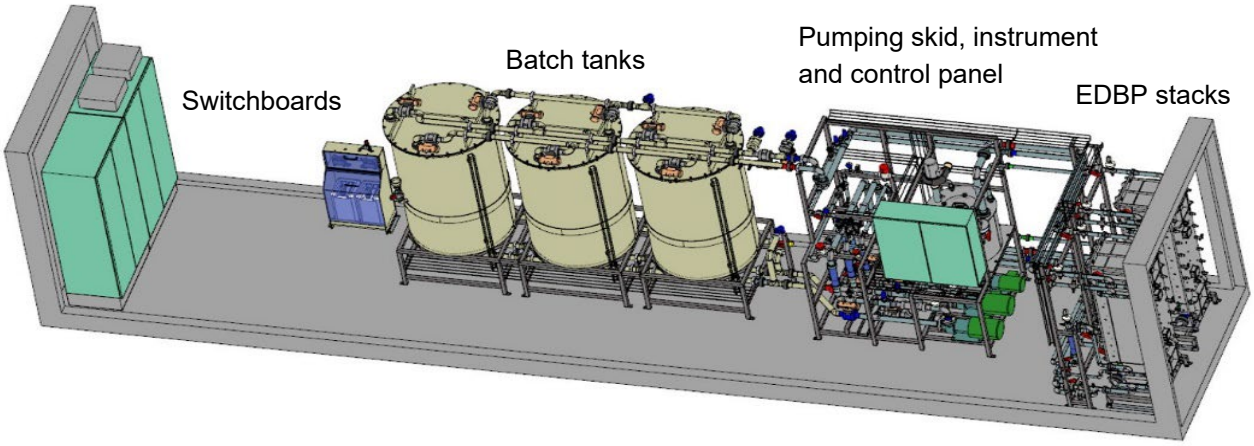

Figure 10: Layout of ELPU-P15 unit in the container

The far left side of the figures show the switchboards which control the appliances; the EDBP pumps, the applied current/voltage on each stack and the ventilators. The two EDBP stacks are located on the right side of the figures. Immediately to the left of the stacks is the pumping skid which includes the human machine interface (HMI), instrumentation and control cabinet. In the middle of the figures are the batch tanks, three 1500 litre tanks (height 1.6m, diameter 1.08m).

The complete EDBP system assembled by MEGA in their factory is shown in **Figure 11**.

Figure 11: Complete EDBP system. Foreground are the two EDBP stacks, EDBP circulation tanks in the middle of the picture and the rectifier cabinets in the background

EDBP IF stacks

The whole EDBP system is based on the two parallel EDBP-IF stacks, both with a nominal capacity of about 100 tonnes CO_2/annum. The system can work with one or two stacks together. In SMART-DAC the capacity is expected to be lower by approximately

25% due to the high concentrations of K_2CO_3 (as feed) and KOH (to be recovered). This will lead to a total capacity of the EDBP section of 150 tonnes CO_2/annum.

It should be noted that the capacity of the unit also depends on the current density used for the operation. Lower current density leads to a lower capacity of the unit, but also to a lower energy consumption per tonne CO_2 recovered; and reversed for higher current densities.

The EDBP-IF module is a vertical electrodialysis module designed for electrodialysis with bipolar membranes. It contains membrane bundles which is a structure that consists of regularly alternating cation-exchange and bipolar membranes. These are separated by multi-layer spacers which define the space of the working chamber. To ensure the thickness of working chamber is maintained, chambers are filled with a mesh which also ensures turbulent flow of the working solution within the stack and improves efficiency. The electrodialysis module is fed by a working solution parallel from both end plates. Inlets are placed in the bottom part of the module, and outlets are placed in the upper part of the electrodialysis module. The module is symmetrical and equipped with electrodes made from titanium covered with a layer of platinum. The polarity of the electrodes cannot be reversed as this operation will irreversibly damage the bipolar membranes.

The EDBP-IF module must be kept out of direct sunlight and other adverse weather conditions. The ambient temperature must not fall below 5°C or exceed 40°C as this could damage the membranes. Therefore before installation the container was insulated to help keep the temperature above the minimum requirement. However, during regeneration runs temperatures in the EDBP were found to be rising. Towards the end of regeneration (about pH 7) the power consumption of the process increases due to the lower conductivity of the feed stream (no carbonate or bi-carbonate remaining). The impact of this is to increase the temperature in the EDBP stack. It was decided that this effect was most likely induced as a result of having the container insulated and with measured temperatures approaching 40°C a heat exchanger was installed to control temperatures and prevent potential damage to the membranes.

Cooling is achieved by using the circulation loop from the MGA unit. The circulation flow is re-routed via the heat exchanger to the tank set cooling the EDBP. This way no extra pumps or other energy consuming devices are required, except for a few valves.

On the EDBP side one of the loops is used for cooling. The concentrate loop was chosen because this loop does not contain CO_2 and the piping could easily be modified. Again this comes at no energy penalty as the recirculation loop requires no extra pumps or other equipment except for some of valves.

1.2.1 EDBP Operation

To obtain the highest efficiency the ED operation is selected to run in batch mode. A regeneration batch cycle has completed when the content of the acid compartments recirculation vessel has changed from a K_2CO_3 solution into water and the content of the base compartment recirculation vessel has changed from water to a 1-2 molar KOH solution. On completion of a regeneration batch cycle the base compartment's recirculation vessel must be emptied, and its content sent to the MGA unit to be used in the absorption cycle and the vessel to be used for the next regeneration. It is not necessary to empty the acid compartments recirculation vessel, now containing water,

as it is used as the starting fluid for the base compartment's recirculation vessel in the next regeneration batch.

To enable starting a new regeneration batch while the current (finished) base compartment's recirculation vessel is being emptied, an extra empty vessel is required within the ED unit to serve as the new acid compartment's recirculation vessel to be filled with new K_2CO_3 solution from the K_2CO_3 'day tanks' for the next regeneration batch. By using 3 tanks within the EDBP unit there is always an empty vessel available to fill with a new K_2CO_3 batch serving as the acid compartments recirculation vessel.

1.3 Tank set

The buffer system has been designed to serve both the circulation of absorbent over the MGA modules and the circulation of loaded absorbent over the EDBP system to regenerate the KOH for reuse as absorbent as well as to release the CO_2 from the K_2CO_3 solution at the same time.

The buffer tanks A, B and C (**Figure 12**) have a size of $5m^3$ each and the three EDBP tanks can contain up $1.5m^3$ each.

The large capacity of the buffer tanks allows the collection and storage of lean and loaded absorbent enabling the use of the EDBP at a higher capacity and in periods of low electricity prices.

1.3.1 Design of the tank set

The MGA absorption liquid is stored in the tanks of the tank set and is designed to allow the MGA process to operate continuously. At the moment the liquid is saturated circulation switches to the next tank. The third tank is an additional buffer to facilitate the constant and efficient filling and emptying the tanks.

The tank set is made up of three parallel installed tanks. Each tank is equipped with two automatic feed valves and two automatic discharge valves and a manual drain valve. To prevent short cuts, feed connection is located at the rear and discharge connection at the front. A manhole is located at the front side to allow access if required. (**Figure 12**)

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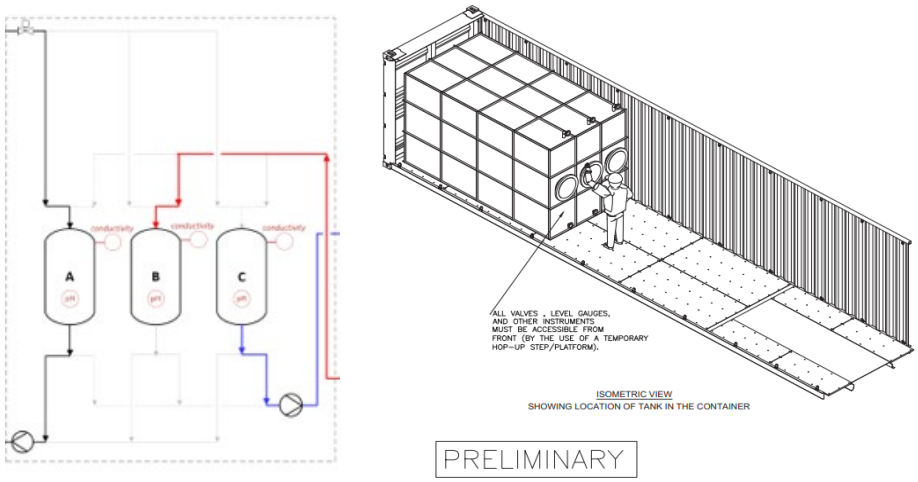

Figure 12: Drawing of tank set with flow diagram

The tank set has been installed in its own 40ft container. A bund has been installed to capture any discharge due to leaks and all pumps and electrical equipment have been installed above ground level as a safety precaution.

1.4 Measurement System

This summary details the implementation of a CO_2 liquefaction and flow measurement system designed to support the SMART-DAC unit operations. The system includes the following key components:

- Two 20m^2 gas bag buffer storage
- a gas flow meter
- an automated pneumatic booster unit, incorporating two air driven gas boosters
- associated air compressor (including compressor, air receiver and chiller)

These elements work together to regulate and measure the flow of CO_2 gas before its liquefaction, ensuring efficiency and consistency in operation.

The system was installed in this configuration to avoid the need for gas chilling. Instead of relying on refrigeration, the pneumatic booster increases the CO_2 pressure to up to 70 bar, allowing liquid conditions to be achieved at ambient temperatures. This approach simplifies the system design and reduces energy consumption associated with traditional cooling methods. To ensure the quality of the CO_2 supply, moisture traps were added to the feed pipework to remove water from the saturated CO_2 gas. The presence of moisture can lead to operational issues such as ice formation, corrosion, or contamination in the liquefaction process. The moisture traps help mitigate these risks by effectively capturing and eliminating excess water before the gas enters the booster and downstream components. The gas bag buffer storage helps manage fluctuations in gas supply, providing a stable flow to downstream processes. The gas flow meter enables accurate measurement of CO_2 flow rates, ensuring precise monitoring and data collection. The automated pneumatic booster, powered by an air compressor, increases the pressure of the CO_2 gas as needed to facilitate the liquefaction process.

One of the primary challenges encountered during the implementation phase was that the inlet gas pressure was lower than initially specified and anticipated. This discrepancy led to difficulties in achieving the desired flow rates. However this issue was overcome by installing an additional valve upstream of the gas meter and modifying the pneumatic booster set up for a higher capacity inlet of driven air.

Ongoing monitoring and analysis is being conducted to evaluate the system's performance and identify potential refinements. Further improvements, such as modifications to the inlet gas supply or adjustments in booster settings, are under consideration to ensure stable and efficient operation.

Overall, the CO_2 liquefaction and flow measurement system has been successfully implemented,

2 Pilot Plant Performance

2.1 Testing and operation program

The pilot plant was ready for testing and operation after commissioning and system testing 17 months into the project in August 2023. Apart from a couple of periods to carry out essential maintenance and installation of equipment the pilot plant has shown significant up time from start-up to the end of the project. The operational running time has been around 80%, which is extremely high for a pilot-plant.

The pilot plant has been built in stages with capacity being added throughout the project. Therefore, the reporting of the performance of the pilot plant has been split into stages as described in **Table 1** below. Module types fixed and free refer to the header frame and base plate designs described in **section 1.1**

Period	Dates	MGA modules	Module Type	MGA operational days	EDBP Stacks	Stack type	EDBP operational runs
1	Aug23-Nov23	2	Fixed	58	1	Ralex	44
2	Feb24-May24	4	Fixed	128	1	Ralex	102
3	Jun24-Aug24	8	Fixed/Free	85	1	Ralex	118
4	Aug24-Oct24	9	Fixed/Free	45	1	Ralex	107
5	Oct24-Jan25	4	Free	92	1	Ralex	409
6	Feb25-Mar25	1	Free	59	0.5/1	New /Ralex	160

Table 1: Summary of testing periods and operational set up

The objective of the testing and operation programme was to optimise operational parameters to enable setting the system to run continuously and automatically. In the 1st period the controls of the buffer system were not fully operational. The system was optimised during periods 2 & 3 resulting in fully automatic control of MGA and EDBP from period 4 onwards with the addition of the full smart buffer control from February to March 2024.

In the time between periods 1 and 2 (8 weeks from December 2023 to January 2024) no operation was possible due to a sensor problem in the EDBP unit which meant the system needed to be shut down to prevent potential damage to the EDBP stacks.

During testing the following parameters were kept constant;

- KOH concentration 1.5 molar (mol/L)
- MGA membrane inside fluid velocity 0.3 m/s
- EDBP membrane stack flow 5.5 m^3/h
- Max voltage EDBP 260 V (limited by grid capacity)

2.2 Measurement results and analysis

This section will focus on measurements taken in periods 5 and 6. In periods 1-4 the focus was on system optimisation and experimentation with differing setups. Also the measurement system was not fully in place so capture rates and produced CO_2 are less accurate.

2.2.1 Period 5 October - December 2024

During period 5 only container 2 was operational with four 'free' membrane MGA modules as previous tests had shown that the flux for the 'free' modules was substantially higher than the fixed ones.

The MGA was operational for 92 days in this period. This period also coincided with some severe weather conditions including Storm Darragh which is clearly visible in in the impact which it had in the flux rate (batch no.340) as seen in **Figure 13**.

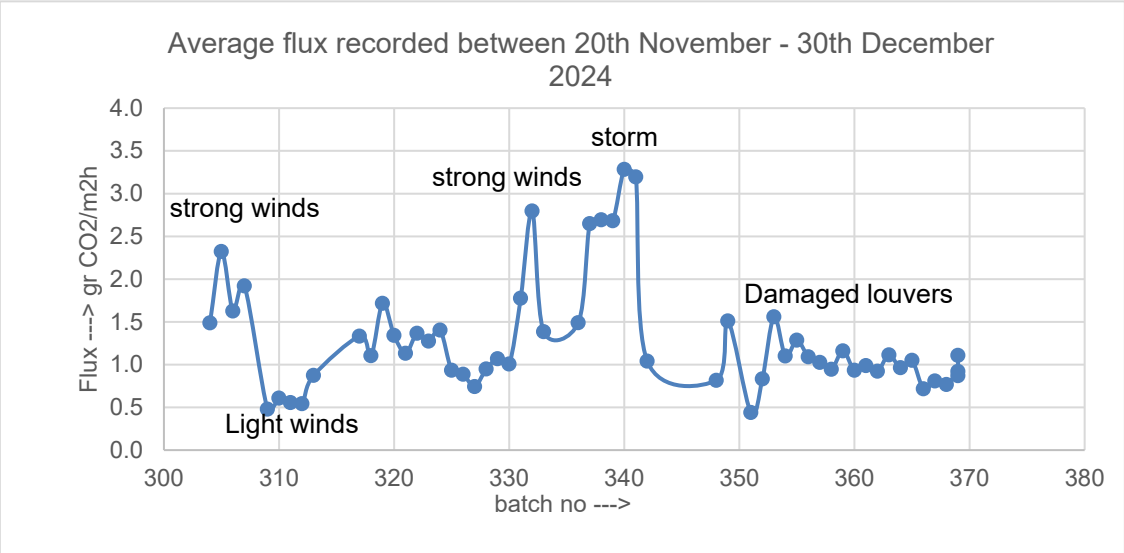

Figure 13: Measure of flux rate in 'free' modules of container 2 with 1.5M KOH

Figure 13 clearly shows the impact in the strength of the wind on the flux rate and absorption of CO_2 by the MGA modules. Batches 300-310 were run between 20th–26th November. In this period average wind speeds were measured between 14-23mph (Weather in November 2024 in Larne Port, Northern Ireland, United Kingdom) resulting in strong flux rates of above 1.5. Batches 310-330 run between 26th November to 4th Dec show lower flux rates. At the start of this period average wind speeds dropped to around 5-7mph (flux 0.5-1) before increasing at the end of November beginning of December to 9-17mph (flux 1-1.75). Batches 330-340 were recorded between 4th-7th December during Storm Darragh where wind speeds increased significantly leading to high flux rates. During the storm the flux rate peaked at 8grCO_2/m^2/h but this point has been removed from the graph for display purposes. The storm caused considerable damage to the louvers which limited the airflow through the container even though, after the initial lull after the storm, average recorded wind speeds were in the region of 10-20mph. This is reflected in batches 350-370 where flux rates of 1.5 or higher would have been expected

based on previous recordings instead of the flux readings of 1grCO_2/m^2/hr or lower recorded.

Chemical analysis based on conductivity and pH measurements combined with laboratory calibration graphs and analyses showed that the average flux during period 5 was 1.5 and recorded greater than the required flux rate during the Storm Darragh (period 5 max), **Table 2**.

Period	Average flux gCO_2/m^2 /h	Effective Membrane area m^2	Container	CO_2 m^3/d	Operational days	Captured CO_2 (kg)	Estimated total CO_2 captured per year (tonne CO_2/yr)
5	1.5	3096	2	111.5	87	9697	77.44
5 max	3.2	3096	2	237.8	5	1189	165.20

Table 2: MGA results period 5 (October – December 2024)

The effective membrane area refers to the total usable membrane area in the 4 active modules. This is considerably less than the design calculations of 7170m^2 (8-9 modules) to capture 100 tonnes per year. Therefore the estimated total CO_2 captured per year is a calculation based on the recorded average flux and the assumptions of 300 working days and 7170m^2 of effective membrane area. Applying this calculation to the recorded average flux demonstrates that theoretically 165 tonnes CO_2/yr would have been captured if an average flux of 3.2gCO_2/m^2/h was sustained throughout the year.

Period	Operational runs	Power kWh/kg CO_2	Water loss %	produced CO_2 (kg)	time per run (mins)	Estimated total CO_2 produced per year tonne CO_2/yr
5	409	4.8	4.3	3681.0	45	86.4

Table 3: EDBP results period 5 (October – December 2024)

As the EDBP unit is not directly impacted by weather conditions, period 5 in the table above is a combination of periods 5 and 5 max.

Similar to the estimated total CO_2 captured per year the estimated total CO_2 produced per year is an estimation based on the recorded results using the following equation;

complete plant =((produced kg CO_2 / (runs*time))*60 min/hr * 7200 hr/yr)/1000 kg/tonnes= tonnes CO_2/yr

As can be seen in the table there is a discrepancy between the captured CO_2 and the produced CO_2. It was during this period that it was discovered that the regeneration process is only releasing approximately 30%-50% of the captured CO_2 due to issues with the gas/liquid separator.

2.2.2 Period 6 January - April 2025

In period 6 a new 'free' type module was installed in container 1 and run with the remaining 3 operational modules in container 2. The fourth module in container 1 was located behind damaged louvers blocking the flow of air to the module so was not used.

The tests in this period were significantly hampered by the damaged louvers which prevented quality data from being detected. Storm Eowyn (24th January 2025) caused further damage to the louvers further impacting the airflow to the modules until effective repairs could be made at the start of February. Although there were strong winds at the start of February these tended to close the louvers preventing sufficient air flow to the modules, meaning flux rates recorded were not reflective of the achievable capture rate for the environmental conditions. Ultimately it was decided to operate the louvers manually (post batch 420, **Figure 14**) and during these times representative data was returned with flux rates above 100 tonnes/annum achieved with wind speeds of around 10m/s or 22mph (batches 430-460). The average wind speed between batches 460-500 dropped again with wind speeds recorded as low as 2mph at the beginning of April. A final test on the 17th April (batches 509 and 510) showed encouraging results with flux rates above 2 recorded at average wind speeds of 7mph. The tests compared the flux rates of modules in container 1 (the lower container) and container 2 (upper container). Flux values above 2 were recorded in the upper container while values below 2 were recorded in the lower container. This may indicate that SMART-DAC performs well at lower than predicted wind speeds when the modules are at height and not obstructed. The site is lined by small trees which may impact the free flow of air to the lower container but do not obstruct the upper container.

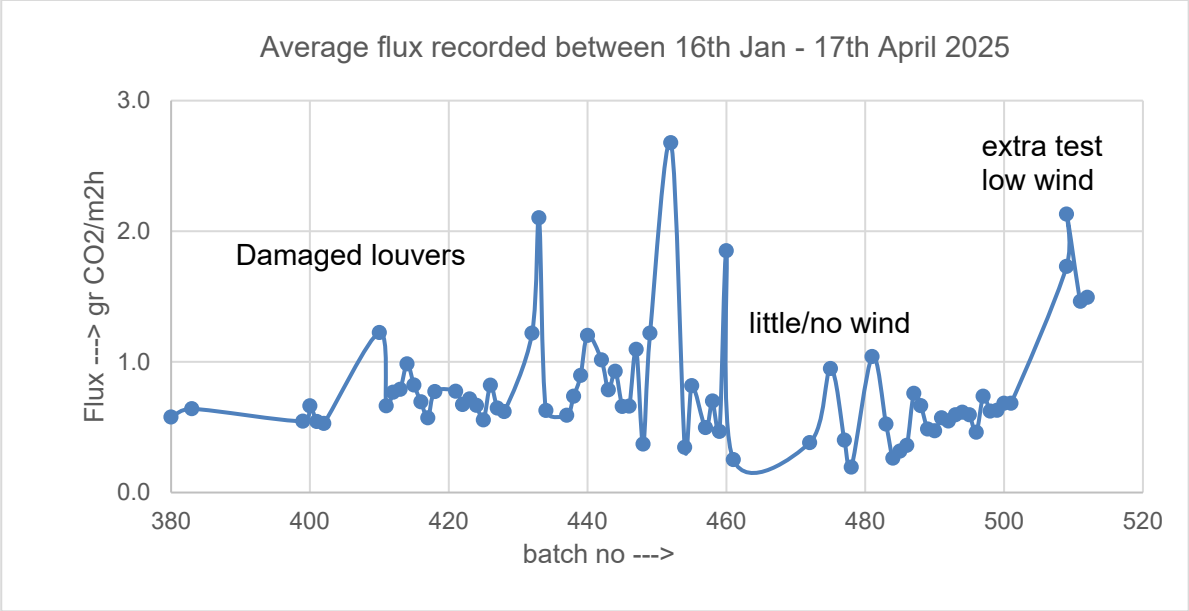

Figure 14: Average flux rates between 16/1/2025 and 17/4/2025

The other key activity which was performed in this period was the collection of over 300 samples from the MGA and EDBP sections to analyse and verify the CO_2 uptake and release in the EDBP.

The analysis and mass balance calculations clearly showed that there is a considerable loss in CO_2 across the EDBP section caused by transport of CO_2 from the "diluate" (H+ side of the EDBP membrane) to the "concentrate" (OH- side of the EDBP membrane).

The CO_2 that enters the concentrate will be transferred back into carbonate (CO_3) by reaction with the OH produced by the EDBP membrane.

These losses strongly influence the amount of CO_2 measured by the flow meter installed after the EDBP section.

The analysis shows that losses can be up to 30% in the EDBP stacks installed in the pilot plant. A different EDBP stack, with thinner membranes, was also installed and trialled during this period but tests showed that it was less robust than the original membranes with up to 50% losses and it was unable to process the CO_2 gas flow released at the end of regeneration runs. The part release of CO_2 is clearly demonstrated by the analysis from run 1038 shown in Figure 15.

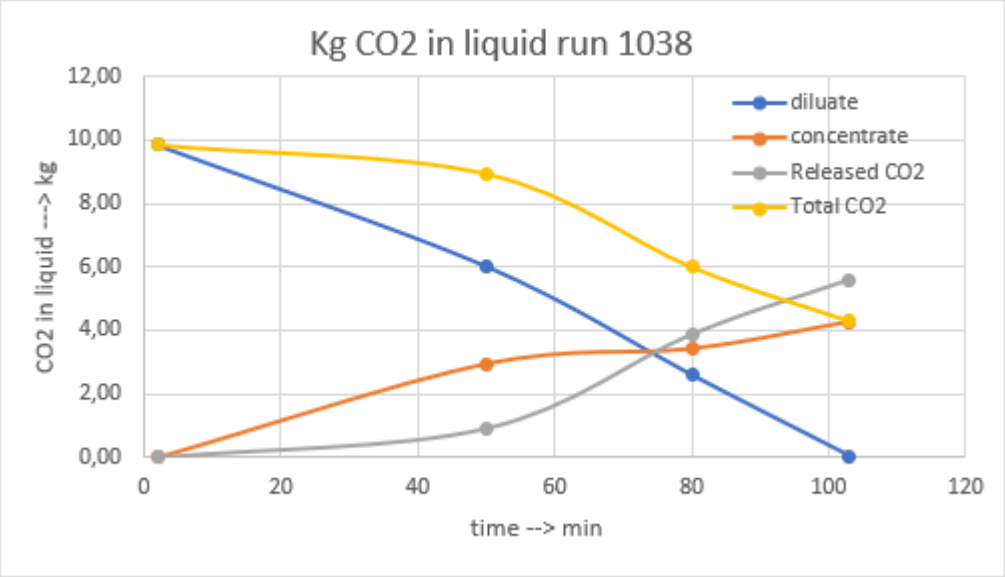

Figure 15: Mass balance of gas release

The graph shows that there is a slow release of CO_2 to start (grey line) followed by rapid production of CO_2. The orange line shows the CO_2 remaining in the concentrate, approx. 40% in this example. The slow release of CO_2 at the beginning of the regeneration is also thought to have an impact on the measured CO_2 produced. Until the production rate increases the flow is not sufficient to activate the installed flow meter therefore it is not recording the total amount of CO_2 produced.

Tests were also carried out at varying loads and flow against the membranes to understand the energy consumption of the EDBP. A lower ampere results in a lower energy consumption but a longer run time. The tests showed a power requirement of 4.8kWh/kg of CO_2 produced.

Considering that 30-50% of the CO_2 is being retained in the concentrate and not being released this accounts for a higher than expected power consumption based on the amount of produced CO_2. Reduction of these losses by improving the EDBP performance and/or the CO_2 recovery process will lead to a lower (potentially up to 50%) power consumption.

The EDBP performance was one of the unknowns at the start of the project as this was a novel application for the system. While the implementation was partially successful the pilot plant demonstrated the potential of the technology and further work on the EDBP

process to resolve the full release of CO_2 and optimise power consumption and flow rates of the stacks are key components of the future work plan for SMART-DAC.

3.3 Summary of results

Period	Dates	MGA Captured CO_2 kg	EDBP Released CO_2 kg	MGA operational days	EDBP runs
1	Aug23-Nov23	1036	385	58	44
2	Feb24-Jun24	4202	891	128	102
3	Jun24-Aug24	4744	1031	85	118
4	Aug24-Oct24	1484	963	45	107
5	Oct24-Dec24	10886	3681	92	409
6	Jan25-Apr25	2572	1440	59	160
Total		**24924**	**8391**	**467**	**940**

Table 4: Volumes of CO_2 captured and released during the project

From the start of testing in August 2023 to the end of the project in March 2025 the pilot plant showed an impressive up time of 467 days (80%) capturing a total of just under 25 tonnes of CO_2. During this period the capacity of the pilot plant was gradually increased from two MGA modules (period 1) to a maximum of nine modules in period 4.

Approximately one third to the total captured CO_2 has been produced. This reflects what was discovered during operation in that there is a considerable loss in CO_2 across the EDBP section caused by transport of CO_2 from the “diluate” to the “concentrate”. These losses strongly influence the amount of CO_2 measured by the flow meter installed after the EDBP section.

With the absorption capacity dependent on the wind velocity understanding the performance and flux rates in relation to wind speed was a key part of this study. The pilot plant was designed to achieve a CO_2 capture rate of 100 tonne CO_2/year (mean of 13.1kg/h) with a total average wind velocity of at least 3-5 m/s (7-11mph) at a recovery of 25-50% CO_2 from the air stream.

Due to some abnormal weather conditions and two of the worst storms in recent years a continuous analysis throughout periods 5 and 6 was not possible. The storms severely damaged the louvers installed in the pilot plant which limited the flow of air to the MGA modules. However data recorded in November and during Storm Darragh is very encouraging showing flux rates in excess of $2grCO_2/m^2/hr$ being achieved at average wind speeds of 8-10mph and approaching $3grCO_2/m^2/hr$ towards the end of November where average wind speeds were recorded between 15-23mph. Extrapolating the average flux rate measured in period 5 over a year and assuming a total membrane area of $7170m^2$ (8-9 modules) the total CO_2 captured would be 165 tonnes.

Maximum flux rates were achieved during Storm Darragh but due to the damage caused the flux rates measured post the storm are unrepresentative. Investigation of the average wind speeds post storm shows that they ranged between 8-20mph indicating that if it had not been for the damage SMART-DAC would have been capturing for a sustained period at or over 100 tonnes CO_2 per annum.

Similarly tests carried out between January to April 2025 show that when there is free air flow to the membranes the required flux rates are achieved for wind speeds above the required threshold.

Batch tests 509 and 510 on 17th April showed that a flux of greater than 2 was achieved with an average wind speed of 7mph. Lowering the threshold to this would result in SMART-DAC capturing at over 100 tonnes per annum for just less than 70% of the time.

However, the wind data also shows multiple periods of where wind speeds dip below 6mph indicating periods of gentle winds. These are most evident in November 2024, where wind speeds were generally low, December 2024 post Storm Darragh, January 2025, March 2025 and April 2025.

While SMART-DAC is still capturing CO_2 at these wind speeds the measured flux rates indicate that they are not sufficient to capture CO_2 at a rate of 100 tonnes per annum considering the design of the pilot plant. Therefore further research is required into the design and performance of the MGA modules to improve capture rate at low wind speeds and SMART-DAC's suitability in diverse environments.

A liquefaction system was installed and used to process and bottle the captured CO_2, demonstrating the full end to end value chain of capture and processing. The captured CO_2 was analysed giving a measured purity of 98.456% with water as the main impurity.

3 Successes and lessons learned

Through the GGR Programme the SMART-DAC technology has been accelerated from concept design through to demonstration in the field taking the technology from TRL3 to TRL 6/7.

SMART-DAC is one of the first DAC systems operating and capturing CO_2 in the UK. With first CO_2 captured in September 2023 it has had an operational uptime of > 80% over a 19 month period to April 25. During this time the system has demonstrated rates of capture at times in excess of 100 tonnes per annum.

Based on the data recorded and data analysis it is projected that it is possible to reach an energy consumption of less than 2.5kWh per kg of CO_2 captured. Using these projections for scaling up to a 10,000 tonnes per annum plant production costs of green CO_2 around £300 to £500 / tonne should be achievable.

Some of the key results and findings are:

- The technology successfully captured CO_2 through natural processes and without mechanical intervention, separated out the CO_2 from the absorbent and the absorbent was regenerated for reuse
- A fully automated and programmable system has been developed allowing SMART-DAC to be accessed and run remotely
- The absorption membranes were shown to be very robust, surviving severe weather conditions including two of the worst storms the UK has experienced in recent times
- Freezing during the winter months was not an issue, with only a handful of days when the temperature dropped below zero. However snow in January did cause tangling of the membranes. This occurred after the louvers had been damaged by the storms so would have been avoided if a fully operational system was available to shut the louvers and protect the membranes.
- The MGA module design needs to be improved to be more effective at low wind speeds and easier to access in order to carry out repairs
- The louvers selected to protect the MGA modules from sunlight and wind worked well to protect the membranes from UV light but the mounting and construction proved not to be robust enough for strong winds. Operation, type or construction needs to be re-designed / re-engineered taking into account reduced wind resistance and reliable UV protection.
- Evaporation of water in the pilot plant seems to take place at a constant rate of 1-2 litres/hour, considerably lower rate than during tests in the laboratory
- At a number of modules the wetting of membrane fibres resulted in a leakage rate (about 2-3 litres/module/hour). This flow is collected and returned for reuse in the MGA-tanks, and has stayed more or less constant over the latter stages of operation.
- From the speed of pH reduction it can be concluded that the use of regenerated vs. fresh absorption liquid gives a similar MGA performance
- During the regeneration runs temperatures in the EDBP were found to be rising. To regulate the heat CO2CirculAir chose to install a heat exchanger in the pilot-plant. Since installation, temperatures have been controlled allowing multiple regeneration runs.

- The design and technology within SMART-DAC appears to be very robust and unaffected by periods of shut down and start up. The plant was shut down for a period of 10 weeks and from Dec 23 – Feb 24 and restarted without any issues
- Data gathered and advancements in the EDBP plant have allowed for a vast improvement on absorbed power.
- Measurement of the transport of CO_2 between sections in the EDBP highlights that not all the CO_2 is being released and therefore measured by the flow meter installed after the EDBP section. CO2CirculAir are collaborating with the membrane manufacturer to research the cause and develop a solution.

Remaining uncertainties and future development

- The MGA unit:
  - Review of module design to improve absorption capacity at low wind velocities and increase absorption area per container
  - Module design and configuration needs to be reviewed to allow better access for maintenance
  - Optimise and improve CO_2 mass transfer coefficient reducing size and costs of absorption section
- The EDBP unit
  - Optimise operation to further reduce the specific energy consumption
  - Improvement in the performance of the EDBP stacks, specifically the release of CO_2 during the regeneration process

- Review louver design concept and construction to withstand high winds and protected against UV light while not adversely impacting flow of air across the membranes.

4 Measurement, Reporting and Verification

4.1 Measurement and Control

4.1.1 MGA Unit

Lean KOH solution has a pH value ranging between 12 and 14. When KOH is converted to K_2CO_3, the pH range lowers to a range of 10 to 12, whereas when $KHCO_3$ is the main component pH lowers further to around 8 (see figure below). By measuring pH, the process is monitored and controlled with respect to the desired main component K_2CO_3 or $KHCO_3$. The final MGA product composition (ratio K_2CO_3:$KHCO_3$) depends on the residence time given for CO_2 absorption; in MGA batch-mode this means a dependency on the amount of recirculation.

Alternatively electric conductivity measurements are used. These have a faster and more sensitive response to process changes and hence are preferred for MGA process control.

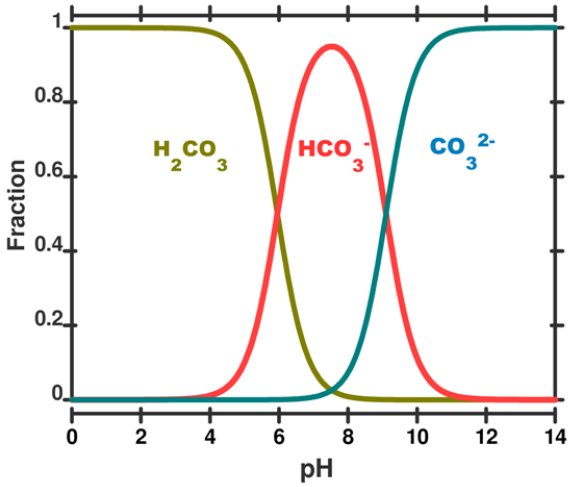

Figure 16: Distribution of CO_2, bicarbonate and carbonate vs pH

Flow rate and pressure of the absorbent into the MGA module are also measured. Pressure within the MGA unit is controlled by a valve installed behind the last MGA module. This valve controls the pressure within the MGA unit including the recirculation systems.

Conductivity is used to determine concentration per batch which is highly dependent on the temperature. A temperature measurement in the EDBP was used as this corresponded well at the start and at general outside temperatures.

4.1.2 EDBP Unit

This effluent stream is measured with respect to

- mass flow rate and
- CO_2 content (weight fraction)

These are key measurements within the monitoring plan and important measurements as they indicate the amount of CO_2 captured and released during operation of the pilot plant.

Measurement of mass flow rate

The flow rate of CO_2 is measured at various stages with the final measurement of CO_2 produced taken at the point of liquefaction as this is the end point of the process. Losses of CO_2 during the absorption and regeneration steps, if any, are only an indication of the efficiency of the operation.

The MGA modules have been designed for optimal capture at wind velocities of around 3-4 on the Beaufort scale, meaning that the overall capture in the module takes place with a driving force of 300 ppm CO_2 (entrance with 400 ppm, exit at 200 ppm). At lower wind velocities the module may capture less CO_2 ,at a lower exit concentration, and therefore at lower efficiency. At higher wind velocities the efficiency of the module may be higher, with a higher exit concentration of CO_2.

To measure the total amount of CO_2 captured and recovered in the EDBP step a gas flow meter has been installed of type ASCO MF 15 or MF 25. This flowmeter was selected as it has been developed to accurately measure CO_2 gas flow in closed pipes.

Measurement of CO_2 content (weight fraction)

Impurities in the gas flow to the liquefaction system are removed during the process, either by condensation (the water content might be up to 2%, depending on the ambient temperature) or, if necessary, by active carbon absorption before liquefaction (not installed). For control of the composition of the produced CO_2 samples are analysed.

Measurement of energy consumption

To determine the electrolysis power supply, voltage, current, and duration are continuously monitored and measured.

The monitoring of the EDBP regeneration system is included in the control panel of the EDBP unit as manufactured and delivered by MEGA. The variables measured by the system include: Temperature (C), Voltage (V), Current (A).

The heart of this system is controlled by a Siemens 7KM4212-0BA00-3AA0 SENTRON PAC4200 Multifunctional Meter 3x 690/400 VAC. In this system all the measured information from the sensors located within SMART-DAC is collected to be downloaded for verification and recording.

The total power input (kWh) for the pilot-unit is measured through the connection installed at the trial site. The power usage to the pilot plant is recorded separately from the rest of the site with the difference between the total power input and the power as measured in the EDBP unit accounting for the power input used for the pumps and remaining equipment (RO unit, instrumentation) of the total pilot unit.

4.2 Life Cycle Analysis

A life cycle analysis (LCA) was undertaken and implemented following the principles and guidelines provided by ISO 14040 to ensure the reliability and accuracy of the results.

With the pilot plant in Larne being built as a test centre as well as a demonstrator it has been over designed to include the testing facilities. It was therefore decided to calculate the LCA on the designed specification for a 10,000 tonnes per annum commercial plant.

The LCA considered materials, manufacture and operations. End-of-life and use of the CO_2 (utilisation or storage) were not considered as this was not a requirement of the project. Data collection used both primary and secondary sources. Primary data on materials and components and plant performance was supplied by CO2CirculAir and from the next stage design study carried out by Process Design Centre (PDC). Where data was not available it was sourced from secondary data sources such as literature, industry reports and databases to ensure comprehensive coverage.

The SMART-DAC process is in principle a closed "box" with input of CO_2 from the air on one side and an output of a concentrated clean CO_2 stream on the other side. The CO_2 is absorbed in a KOH stream by Membrane Gas Absorption (MGA) and released in the next step by electrolysis (EDBP) in pure form. The absorbent is regenerated in this last step. The only other input into the system is energy in the form of, preferably green, electricity for the regeneration section, the pumps to transport the lean and loaded absorbents to and from absorption and regeneration section, and instrumentation. **Figure 17** below shows a summary of the initial boundary conditions considered in the LCA.

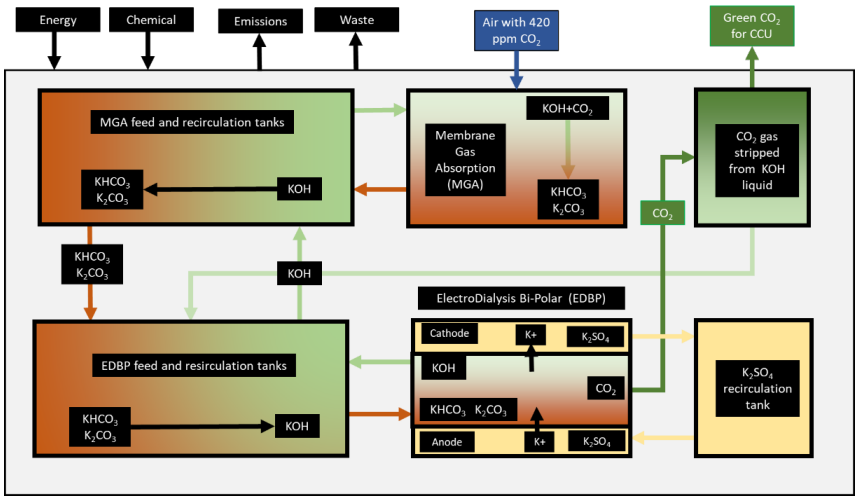

Figure 17: Initial boundary conditions for the LCA

Emissions to air, water and soil are negligible. The SMART-DAC system is "a closed box" that takes in CO_2 from the air through the MGA unit and releases the captured CO_2 in the regeneration section. All other fluids are recirculated within the system.

Emissions to the air are restricted to the evaporation of water in the MGA section (see below). Evaporation is suppressed as far as possible by the addition of an additive to the circulated absorbent. All additives used in the absorbent have no or very low vapour pressure at ambient temperatures.

There will be no emissions to surface water because the plant does not have any connections to a sewage or drainage systems.

Emissions to the soil and ground water are prevented with the installation of bunds with sufficient capacity to capture any leakage and preventing it from reaching the ground.

Although evaporation of water will be restricted as much as possible it is expected that there will be some loss of water through the pores of the membranes in the MGA section.

With the pilot plant in Larne being built as a test centre as well as a demonstrator it has been over designed to include the testing facilities. It was therefore decided to calculate the LCA on the designed specification for a 10,000 tonnes per annum commercial plant.

Figure 18 outlines the LCA framework considering the process for emission calculation. The LCA study found that the main factor affecting the impact was the source of the electricity. Hence, two scenarios were investigated: (i) electricity from 2024 grid energy NI and (ii) using wind generated electricity only.

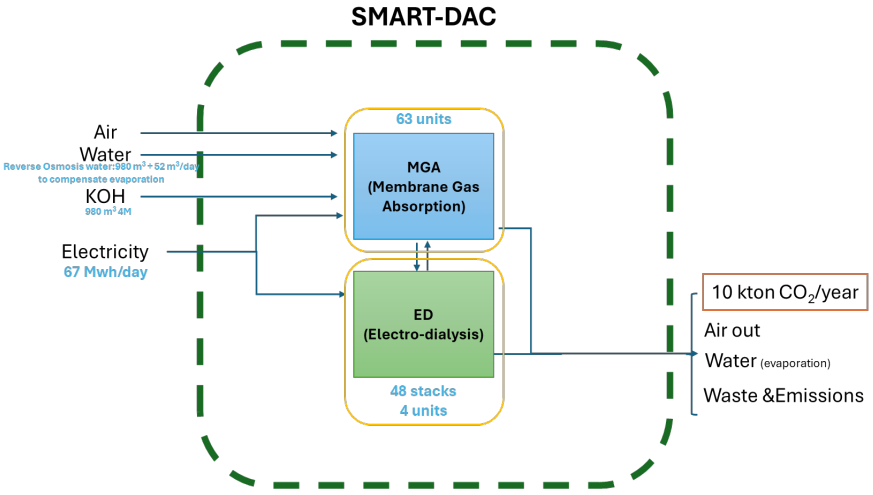

Figure 18: LCA framework considering the process for emission calculation

Table 8 summarises the findings of the two options. Since 2024 the grid distribution in Northen Ireland has been 45% renewable energy (mainly wind) and 55% non-renewable energy (mainly natural gas) the grid option came out at 17% efficiency. This is no surprise and when the 100% renewable energy was considered, as the plant is designed to be run, the SMART-DAC process achieved an impressive 88% efficiency. In summary

- Electricity from 2024 grid energy NI, in the SMART-DAC process, 1 kg of CO_2 captured emits 0.832 kg of CO_2
- Using electricity produced 100% from renewable source, in the SMART-DAC process 1 kg of CO_2 captured emits 0.124 kg of CO_2 equating to an efficiency of 88%

SMART-DAC CO_2 Captured (kg)	Total process emissions (1) (electricity provided by NI grid, $kgCO_2eq$)	Total process emission (2) (100% electricity from renewbles, $kgCO_2eq$)	Net Difference 1 ($kgCO_2eq$)	Net Difference 2 ($kgCO_2eq$)
10x106	8.32x106	1.24x106	1.68x106	8.76x106

Table 5: Summary of the LCA findings from the two options modelled

5 Techno Economic Analysis

The techno economic analysis (TEA) is based on plant costing data provided by CO2CirculAir for a 10,000 tonnes per annum demo plant design. The plant was assumed to be in Northern Ireland (or more generally the United Kingdom), where relevant location-specific data, including electricity prices and carbon intensity factors, were obtained.

Three economic analyses were undertaken during the project. Heriot Watt University carried out a thorough TEA evaluating CO_2 removal costs for both pilot and demonstration scale plants, including projected Nth-of-a-kind (NOAK) costs based on learning curves. The analysis considered both capital and operating expenses, with distinct specifications for each scale. The purpose of this analysis was to

- to evaluate the scalability potential of the plant through detailed cost assessment
- to compare the economic transition from pilot to demonstration scale plants (TRL 6 to TRL 7)
- to identify cost hotspots in both designs that could guide future optimisation efforts.

Process Design Centre (PDC) completed a TEA using their in-house costing tool (PROSYN) as part of the next stage design process, and CO2CirculAir also made a cost evaluation based on information gained from the pilot plant project results and input from a construction company for a TRL9 installation.

As each of the evaluations used different approaches and methodologies it was thought that this was a valuable exercise to understand the variability and impact of factors on the overall cost per tonne of CO_2.

This section will provide a summary of the results for the evaluations of the 10,000 tonne per annum demo plant.

For the evaluations CO2CirculAir supplied the costs for the key capital equipment (**Table 6**) and an assumed price of renewable electricity of £0.05/kWh.

Capital Cost Elements	Cost (£k)
Electrodialysis Stacks	7309
Membrne Gas Absorber Unit	26401
Balance of Plant (tanks, pumps, utilities, first-fill)	1967
Total	35677

Table 6: Capital cost elements provided by CO2CirculAir

The results for each of the evaluations is shown in **Table 7**. Although CO2CirculAir and PDC took differing approaches the cost per tonne of CO_2 removed came out fairly similar at £390 and £435 per tonne respectively.

CAPEX cost per tonne, OPEX cost per tonne and total yearly cost per tonne is shown only for Heriot Watt as their approach worked on a levelised cost of CO_2 removed and these were the figures presented.

Organistaion	CAPEX, £m	Annual CAPEX (based on 25 years depreciation)	CAPEX cost per tonne CO_2 (£)	OPEX, £m	OPEX cost per tonne CO_2, £	Total yearly cost CAPEX+OPEX (£m)	Total yearly cost per tonne CO2 (£)
CO2CirculAir	35.2	1.4	140	2.5	250	3.9	390
PDC	35.2	1.4	140	2.95	295	4.35	435
Heriot Watt			800		525		1325

Table 7: Cost per tonne comparison for the techno economic analysis performed by CO2circulAir, PDC and Heriot Watt

The differences between the results can be attributed to how each party has assigned contingences and calculation factors as well as the type of installation SMART-DAC has been classified. Both PDC and Heriot Watt have classified SMART-DAC as a petro-chemical plant resulting in higher direct and in-direct costs. CO2CirculAir have instead worked on the assumption that SMART-DAC should be classified as a non-harmful, non-flammable gas producing water based system such as an electromembrane or other type of water based membrane installation.

CO2CirculAir TEA approach

Based on the information in **Table 9** above, CO2CirculAir estimate the CAPEX required for a 10,000 tonne per year plant is £35.6M which gives an annual cost of £1.4M or £140 per tonne CO_2 based on a depreciation period of 25 year. CO2CirculAir have not included the MV/LV works for the power supply and civil works including building. Included is the MGA unit, the EDBP and the balance of plant (the SMART Buffer, utilities, etc…). For the OPEX the main contribution is electricity, which is considered to be supplied by renewable energy at a cost of £0.05 per kWh. Total OPEX is estimated to be £2.5M or £250 per tonne CO_2.

Total CAPEX and OPEX is therefore estimated at £390 per tonne CO_2 for a TRL9 based 10,000 tonne CO_2 per year SMART DAC installation using inputs from the TRL6 pilot plant installation (100 tonnes per year).

PDC TEA approach

PDC has used the CEPCI method which typically reflects chemical process plants such as petro-chemical plants, fine chemical production and oil and gas plants.

PDC have introduced contingencies in the calculations to account for uncertainties and risks in the cost of items. For example in the bare module costs (TBMC) up to 30% contingencies has been applied to the CAPEX.

The calculation also includes additional buildings normally associated with petro-chemical plants which are not necessarily relevant for a SMART-DAC installation. However they have considered that SMART-DAC is fairly simple compared to these type of processes, and have reduced a number of specific cost items meaning that CAPEX and OPEX costs are similar to those calculated by CO2CirculAir.

PDC calculate the annual total cost as £4.35M (5.2M euros) or £435 per tonne CO_2 for a 10,000 tonne per year installation. This is in close agreement to the calculation of CO2CirculAir despite the application of additional indirect costs and treating SMART-DAC as a petro-chemical plant with the associated higher maintenance costs and contingencies.

Heriot Watt TEA approach

Heriot Watt University (HW) have applied an analysis using the plant data (100 tonnes per annum) and adjusted to reflect costs for a first-of-a-kind (FOAK) or TRL9 plant, representing the first commercial scale implementation. The analysis presents comprehensive breakdowns for capital expenditure, operating expenditures and includes the carbon penalty from indirect emissions.

A model is used to calculate the Levelised Cost of CO_2 removal (LCCR) which takes into account the increase in technological readiness level, annualised capital investment, annual operating expenses (fixed and variable), process/project contingencies and annual net CO_2 removed. Heriot Watt also considered the LCCR for a 10,000 tonne plant powered by grid and renewable energy, whereas CO2CirculAir and PDC considered only renewable energy.

A key difference in the calculation is the capital cost assumptions where an annualisation factor is applied increasing costs by at least a factor of 2 compared to dividing the CAPEX by only the life time of 25 years (CO2CirculAir and PDC approach).

Heriot Watt like PDC have classified SMART DAC as a chemical plant and applied contingencies of between 15-30%. This increases the OPEX by at least £1M with additional annual costs. Using grid electricity (£0.09 per kWh) will also increase OPEX compared to renewable energy (£0.05 per kWh).

To calculate the LCCR the annual costs are divided by the annual net CO_2 removed which will be much lower when grid electricity is used. As a result the cost per tonne CO_2 increases significantly when calculated for an installation powered by the grid. However, when considering renewable power the yearly cost per tonne is only about 3 times more than that calculated by PDC and CO2CirculAir at £1,325 per tonne CO_2 .

Analysis of Results

The cost estimations give a pragmatic range of between £390-£1,325 per tonne CO_2 removed for a 10,000 tonne per year SMART-DAC installation.

All evaluations identified the same critical factors for scaling the technology. First and foremost, low-carbon electricity is essential for viable carbon removal economics, as grid electricity generates significant indirect emissions that substantially increase the net cost per tonne of CO_2 removed. While scale deployment will naturally reduce costs through learning curves, the technology faces specific technical challenges: the membrane gas absorption unit dominates capital costs, while the high electricity consumption of the electrodialysis unit drives operational expenses. Focusing innovation efforts on these two components represents the clearest path to achieving economically competitive carbon removal at scale.

With continued research and development in these areas CO2CirculAir believe a cost of <£400 per tonne CO_2 is achievable in reaching TRL9 in 2 years, and values around £200 per tonne are achievable in time as a result of economies of scale and further developments in 5 years.

6 Business Plan

With the development of the SMART-DAC process CO2CirculAir aims at playing an important contribution to reducing the challenge of increasing CO_2 concentration in the atmosphere.

SMART-DAC aims at DAC technology for capture of CO_2 at atmospheric concentrations. Currently the world-wide market for DAC is dominated by three major players: Carbon Engineering (Canada), Global Thermostat (USA) and Climeworks (Switzerland). To date these companies have focused on the capture and storage of CO_2. SMART-DAC however looks to position itself in the market for the utilisation of captured CO_2 as a feedstock for the production of synthetic fuel or in the production of low carbon products to help decarbonise businesses such as the chemical, building, food or horticulture industries. Together is estimated to be a $800 billion business (The Global CO_2 Initiative Roadmap (2016)).

The modularity of SMART-DAC and its flexibility in location makes it an ideal solution for CO_2 utilisation for both small and large scale applications. Being able to locate next to an end user of CO_2 removes the need for transportation removing one of the barriers to widespread CO_2 utilisation adoption. For CO_2 utilisation the DAC process could be fitted to new or existing installations for converting the CO_2 to basic chemical products (e.g. green-methanol or methane) or to directly convert the CO_2 to synthetic fuels (e.g. kerosine for aviation (e-SAF)).

Another direct application is the provision of green CO_2 to agriculture, specifically for use within greenhouses, where CO_2 is used to stimulate growth. The most common method of CO_2 enrichment is via the combustion of natural gas. SMART-DAC would provide a circular system, supplying green CO_2 for use in crop enrichment while removing any emitted and residual CO_2 in the air.

SMART-DAC has been designed around modularity, low cost materials, simplicity of operation and mechanical parts, and the flexibility to harness green energy or when surplus energy is available at low cost, making it an affordable solution to industries where cost margins are low.

At present the development of SMART-DAC is technically in the pilot-plant stage and commercially in the seed stage. In this report a roadmap is given of the envisaged scale-up and route to commercialisation of the technology.

Route to Market

The main plan is to develop SMART-DAC to address particular market segments, specifically

a) Direct use of (green) CO_2 with existing markets such as food & beverage, pharmaceutical and horticulture (replacing the use of fossil generated CO_2)

b) Use as a building block, with new markets like e-fuels* and chemical industry.

* e-Methanol, e-Diesel, Sustainable Aviation Fuel, and other e-fuels

CO2CirculAir have met with a variety of potential partners including not for profit, commercial, Research & Technology and Academic organisations working in these areas to demonstrate SMART-DAC for particular market segments. Potential initiatives and secured projects are outlined below.

- **Marine Fuels / e-Methanol**, CO2Circulair has signed an MoU for cooperation for future developments of the SMART-DAC technology targeting large volume green CO_2 production for e-Methanol (MeOH).
- **Green CO_2**, we also are targeting the CO_2 market for replacing fossil generated CO_2
- **E-fuels**, CO2CirculAir have initiated discussions and a potential collaboration with a company based in Belfast developing technology to produce e-fuels. CO2CirculAir identifies this as a potential route into the e-fuels market, with potential to access the aviation market.

  To further this relationship the pilot plant is being relocated post project to the company's site in Belfast where testing and development of SMART-DAC will continue.

Two other key projects for which funding has been secured are;

- **Horticulture**, with WUR (Wageningen University & Research) and Glastuinbouw Nederland CO2CirculAir are testing the use of SMART-DAC to generate green CO_2 and its compatibility for use in greenhouse applications to stimulate the growth of plants (2025).
- **Green Chemicals**, with Fraunhofer Umsicht, University of Aachen and other partners CO2CirculAir are involved in a project investigating the use of CO_2 captured from air for the production of green chemicals (2024-2027).

Future Development

The SMART-DAC system will require an interim (prototype) step or steps to allow for a full-scale commercial design to emerge that can pass the technical and commercial due diligence in advance of a project Final Investment Decision (FID). A concept design has been completed by DPS for a 1.5kt , 6kt and 10,000 tonne version of the SMART-DAC unit with the aim of advancing the 1.5kt project in Northern Ireland,

The concept designs developed allows for a building block approach to deploy the 1.5kt plant to grow organically over time on site as product developments move to TRL9 stages.

With partners CO2CirculAir is also actively investigating the end user market, and the need for 1.5kt to 3kt plants locally. The end user would use the locally produced green CO_2 to displace the existing quantities of imported grey CO_2 that is supplied to the food and drink sector.

This market is available now but would require a fully commissioned plant to gain client confidence to promote private sector investment.

Most of the component products used within the DAC process are TRL9, and easily available on existing markets. The main learnings from the DAC project in Larne have been associated with the membranes themselves, how they are assembled, installed on site and the conditions they need to operate at full capacity. The 1.5kt concept design includes the introduction of an air cleaning system and different louver system. The data and advancements in the EDBP plant have also allowed for a vast improvement on absorbed power. This however would need to be developed at scale to confirm operating

programmes and real life scenarios when using either off grid power or curtailed wind generation which is the plan for the Randallstown deployment.

Key activities and Key Resources

The key activities for the coming 1-2 years are cost reduction of key equipment mainly focusing on the absorption unit. This includes further development work on the membranes but also module design and engineering to improve the process reliability. Resources are required in membrane process development and engineering.

As well as the technical developments, progress and resources are required to deliver business and finance models, building supply chain relationships and procurement, and understanding the regulatory environment for direct air capture and the use of CO_2. Looking forward to years 3-5, development resources will continue, but more focus will be placed on the manufacturing of SMART-DAC installations and building and executing the pipeline.

Revenue Streams

Main short term (1-2 year) revenue streams are project funding, and to find an investor or project fund to build a pilot unit (min 1.5kt pa) to produce CO_2 with the focus to achieve TRL8/9 and be ready for commercialisation. The required funding will be between £5-9 million depending on the size of the unit. Moving onto years 3-5 installation will be delivered for the first customers, expecting a revenue of £40 million as will be described in the next section.

Financial modelling

Together with the support of Sustainable Ventures a financial model has been developed. In the financial model revenue versus cost are modelled, resulting in profit and loss and net profit and lost projections. Costs are divided in material costs, to realise a SMART-DAC installation, and organisational (such as corporate, marketing & development) costs.

The model shows that in the coming 2 years no revenue is expected from commercially sold SMART-DAC units / systems due to investments required to reach TRL8/9. With only a small amount of revenue expected from the sales of CO_2 produced from the pilot installations, potential losses of £8 million in 2025 and £2 million in 2026 are forecast. With the expected demonstration of TRL8/9 at the end of 2026 revenue is expected from 2027 onwards, from around £50 million in 2027 up to £100 million in 2029. Net profit is expected be £5 million in both 2027 and 2028 and around £10 million in 2029. This means that break-even is projected to be in 2029.

Intellectual Property

A patent application has been filed:

- European patent application for "SMART-DAC process" in the name of CO2CirculAir B.V.
- International PCT application for "SMART-DAC process" in the name of CO2CirculAir B.V.
- Date of submission:
    - 14 June 2023 - European Patent Application No. EP 4 477 292 A1;
        - Date of publication: 18.12.2024, Bulletin 2024/51
    - December 2025 - International PCT Application No. PCT/EP2024/065978 on

- "SMART-DAC process" in the name of CO2CirculAir B.V.

Title: CO_2-absorbent composition and method for CO_2 absorption

Abstract: The present invention relates to an absorbent composition for absorbing carbon dioxide from a gas mixture, in particular from ambient air. The present invention also relates to methods for separating and recovering carbon dioxide from said gas mixture. The present invention also relates to systems for separating and recovering carbon dioxide from said gas mixture.

7 Conclusion and recommendations

Overall, the SMART-DAC project has shown considerable potential in advancing direct air capture technology through its innovative approach. It has made substantial progress in developing a cost-effective and efficient carbon capture system, with very promising prospects for commercialisation and large-scale deployment for both CCS and CCU applications.

Through the GGR Programme, a pilot plant with a design capacity to capture 100 tonnes per annum has been constructed and successfully tested to validate the SMART-DAC concept. The programme has enabled rapid acceleration of the technology from concept design through to demonstration in the field taking the technology from TRL3 to TRL 6/7 and in the process becoming one of the first DAC systems operating and capturing CO_2 in the UK. With first CO_2 captured in September 2023 it has had an operational uptime of > 80% over a 19 month period to April 25.

The pilot plant in Larne, Northern Ireland, has demonstrated a capture rate of more than 100 tonnes of CO_2 per annum with wind speeds varying from as low as 7mph up to 70 mph, showcasing the viability of the system to capture CO_2 in a wide operating window.

Based on the data recorded and data analysis it is projected that it is possible to reach an energy consumption of less than 2.5kWh per kg of CO_2 captured. Using these projections for scaling up to a 10,000 tonnes per annum plant total exploitation costs of green CO_2 of around £400 - £500 per tonne should be achievable. As these figures are based on extrapolated data gathered from the pilot plant, they are very positive and indicate as SMART-DAC is optimised and economies of scale are realised from larger capacity plants this will lead to a reduction in the price per tonne.

Commercialisation efforts focus on the utilisation of the captured CO_2 in various markets, including e-fuels, green chemicals, food & beverage as well as agricultural applications. CO2CirculAir have created strong collaborations with renewable energy partners B9 Energy and Catagen, both in based in Northern Ireland, who are working in these areas to provide flexible, location-specific solutions.

The financial model projects SMART-DAC reaching TRL8/9 by 2026, generating significant revenue from 2027 onwards. Continued innovation and strategic partnerships will be essential for overcoming barriers and achieving large-scale deployment, ultimately contributing to global carbon reduction efforts.

The key findings from the project include:

- The technology effectively captured CO_2 using passive wind-driven Membrane Gas Absorption with nearly zero energy consumption. It then separated the CO_2 through electrodialysis, producing pure CO_2 and successfully regenerated the absorbent for reuse.

- The use of regenerated vs. fresh absorption liquid gives a similar CO_2 absorption performance

- A fully automated and programmable system has been developed allowing SMART-DAC to be accessed and run remotely

- The modular design of the plant allowed for testing different configurations, providing valuable insights into membrane materials, system resilience, and operation in various weather conditions.

- The absorption membranes were shown to be very robust, surviving severe weather conditions including two of the worst storms the UK has experienced in recent times

- To prevent biological growth due to the use of amino acids in the absorbent, installation of a UV disinfection section is being considered in the MGA-loop.

- The design and technology within SMART-DAC appears to be very robust and unaffected by periods of shut down and start up. The plant was shut down for a period of 10 weeks and from Dec 23 – Feb 24 and restarted without any issues

- The produced green CO_2 has a high purity, demonstrating a complete end-to-end value chain of capture and processing. The impurities found were water and/or air. Recent analysis showed a measured purity of 98.456%.

- The LCA study indicates that sourcing electricity from 100% renewable sources can achieve an 88% efficiency in the SMART-DAC process, where 1 kg of CO_2 captured emits only 0.124 kg of CO_2.

Recommendations for future development:

The Membrane Gas Absorption section:

- Review of module design to improve absorption capacity at lower wind velocities and increase effective absorption per module and/or container
- Module design and configuration needs to be reviewed to allow better access for maintenance
- Optimise and improve CO_2 mass transfer coefficient reducing size and costs of absorption section
- Review louver design concept and construction to withstand high winds and protection against UV light while not adversely impacting flow of air across the membranes.

The Electrodialysis section:

- Optimise design and operation to further reduce the specific energy consumption
- Improvement in the performance of the EDBP stacks, specifically the release of CO_2 during the regeneration process